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by Rina Mardiati

Submission date: 03-May-2023 07:07AM (UTC+0700)
Submission ID: 2082534216
File name: 2022_ICWT_BMS.pdf (709.52K)
Word count: 4638
Character count: 23812

Energy Optimized of an Electric Vehicle Battery Management System to Improve Storage Lifetime

Rina Ristiana
Research Center of Transportation Technology, National Research and Innovation agency, West Java, Indonesia
rina008@brin.go.id
0000-0002-7842-1126

Amin
Research Center of Transportation Technology, National Research and Innovation agency, West Java, Indonesia
amin007@brin.go.id
0000-0001-8600-9054

Rina Mardiati
Department of Electrical Engineering, UIN Sunan Gunung Djati Bandung, West Java, Indonesia
r_mardiati@uinsgd.ac.id
0000-0002-3949-7830

Aam Muharam
Research Center of Transportation Technology, National Research and Innovation agency, West Java, Indonesia
aam.muharam@brin.go.id
0000-0001-8803-7999

Abdul Hapid
Research Center of Transportation Technology, National Research and Innovation agency, West Java, Indonesia
abdu019@brin.go.id
0000-0002-0599-4206

Alexander Christantho Budiman
Research Center of Transportation Technology, National Research and Innovation agency, West Java, Indonesia
alex003@brin.go.id
0000-0002-3034-4352

Sudirja
Research Center of Transportation Technology, National Research and Innovation agency, West Java, Indonesia
sudi016@brin.go.id
0000-0003-2868-9930

Sunarto Kaleg
Research Center of Transportation Technology, National Research and Innovation agency, West Java, Indonesia
suna024@brin.go.id
0000-0002-5800-8713

2022 8th International Conference on Wireless and Telematics (ICWT) | 978-1-6654-5122-2/22/$31.00 ©2022 IEEE | DOI: 10.1109/ICWT55831.2022.9935453

***Abstract*— The BMS battery pack of the protection and optimization function has been proposed. The protection function of BMS involves current control to reside within the SOA zone and to improve storage lifetime battery by about 28.11% and reliability. The optimization function with applied LQI control to adjust the battery current by adding an integrator at the module BMS system. The BMS with LQI controller has been to improve storage lifetime battery with eliminate current stepping and getting energy-optimized about 28.87% with considering the battery condition.**

Keywords—Battery Management System, Protection Function, Optimization Function, LQI Controller, Optimized Energy, Electric Vehicles.

I. Introduction

In recent years, electric vehicles become a major priority for the automotive industry and have become an integrated part of the automotive ecosystem. The Electric vehicles have the potential as the best alternative vehicle in preserving a sustainable environment from harmful emissions. Thus, many research initiatives are being undertaken to improve the performance of electric vehicles in the next decade.

Batteries are a power source and one of the important components in electric vehicles. Batteries almost cover about 40% of the cost of an electric vehicle. Typically, rechargeable batteries are used to supply power to vehicle systems and electric motors. Among all rechargeable batteries, a lithium-ion batteries are generally used in electric vehicles. The lithium-ion batteries have high power density, low self-discharge, wide operating range, high cycle life, and high mobility efficiency, making them a good choice for electric vehicle batteries. Along with all the benefits available from these batteries, battery monitoring systems play an important role in preventing failures and improving battery quality ensuring the batteries function properly. This monitoring system is called a battery management system (BMS). Good battery management is the key to the successful development of electric vehicles to improve the performance of electric vehicles.

The BMS is an electronic circuit specially designed to ensure the safety and stability of the battery pack. The battery pack is a combination of several cell modules and each module is a collection of individual cells. Each cell can be charge and discharge at different rates, and each cell has a different operational state. This is due to differences in temperature, health status, and charging status, making it difficult to control the performance of the battery pack. The BMS performs the following functions to manage the battery operation and ensure safety and reliability for the smooth running of electric vehicles over an expected period of life. There is protection in order to prevent operations outside its safe operating area (SOA), monitoring by estimating the battery pack when state of charge (SOC) and state of health (SOH) during charging and discharging, optimization thanks to cell balancing that improves the battery life and capacity, and communicating with other electronic control units (ECUs).

The essence features of BMS are the battery pack protection and optimization. The BMS protected the battery pack by preventing operation outside the manufacturer's cell ratings. It involves current control to reside within the SOA zone and to improve lifetime battery. The BMS indicates optimize the amount of energy than can be derived from the battery, and also how much the battery pack can be charged.

The following research on improving battery lifetime includes: in [1] proposed the battery lifetime management method of estimating residual power and lifetime of lithium-ion battery of ESS system with open circuit voltage (OCV) and SOC calculation. In [2] presents a method estimates the total lifetime of the lithium-ion battery by calculating the total transferable energy corresponding to the selected depth of discharge (DOD) and achievable cycle (ACC) data. In [3] presents a simple methodology for calculating the lifetime of the storage batteries which defines the mode indicators with respect to every hour of the period under consideration. The indicators are necessary for the correct estimate of the number of battery cycles to failure. It is possible to calculate storage battery lifetime. In [4] analyses lifetime battery from the degradation that is experienced by different types of Li-ion batteries. The result is a valuable reference analyzing the profitability of these storage solutions.

This paper proposed the BMS design that has been function to improve battery lifetime by set current control to reside within the SOA zone and get energy optimized with determined battery condition as adopt from [5]. In addition, it also takes into account the difference in voltage and current charging or discharging, and analysis of operational status such as SOC and SOH of the battery. Furthermore, simulation and experimental setup of the BMS were carried out to ensure the battery was functioning properly, obtained a good storage lifetime, and analyzed energy optimization

The rest of this paper is organized as follows; Section II describes the battery management system. It is followed by the energy optimizing technique in Section III. Simulation, validation, and discussion are then presented in Section IV. Section V finalizes the paper with the main conclusion.

II. The Battery Management System

Battery management system (BMS) is the oversight technology of battery pack, which covers: monitoring the battery, providing battery protection, estimating the battery's operational state, optimizing battery performance, and reporting operational status to external devices. The BMS is also intelligent protecting circuit, as shown in Fig. 1. It corporates additional modules such as control circuity, management, and display modules. These modules other than controlling provide real time information of the battery pack.

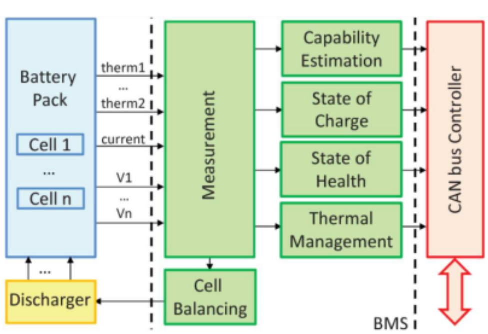


Fig. 1. BMS diagram.

Referred Fig. 1. the BMS allows for constant monitoring gathering, and communicating information to an external interface where observe the status of each cell and health of the battery pack as a whole. The monitoring function of the BMS is measured temperature, current, voltage, and estimated the available capacity of battery. Based on these measurements, the BMS can assess the health of the battery and readjust operations as needed to protect the battery pack. SOC and SOH are important indicators for assessing the usability and capabilities of the battery.

The SOC can show the short term capability of the battery and showing how much energy there is left, but it cannot indicate the true capacity of the battery cell or pack. The SOH measures the long-term capabilities of the battery pack with account charge acceptance, internal resistance, voltage, and self-discharge. The SOH is an estimation of how much longer a battery can operate optimally (lifecycle). Each battery cell and chemistry has voltage, temperature, and current limit range which it can safely operate. When a cell drops below or exceeds the ranges, it can be detected and controller by the BMS. The next feature of the BMS is cell balancing. Individual cells within a battery pack do not operate equally. One cell may be weaker or stronger than the other, charging or discharging faster than others within the chain. Without proper compensation, this could degrade the health of the overall pack. If one cell short circuits or fails, this affects the stability of the whole pack. The cell balancing equalizes the charge between individual cells based on each cell's capability. The BMS helps to monitor and control the charge demanded from each cell in the chain, ensuring that SOC remains evenly distributed.

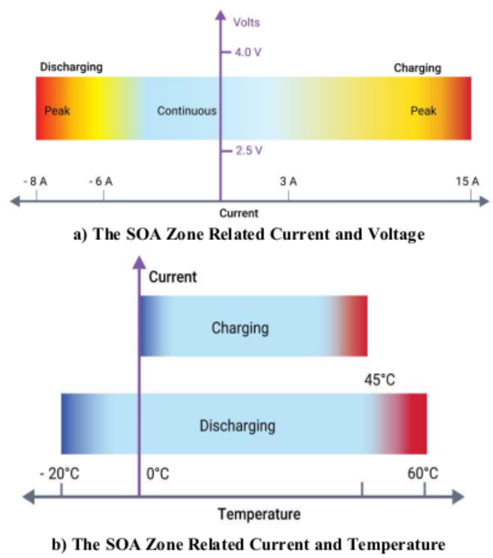


Fig. 2. Lithium-ion Cell SOA.

The essential features of BMS are the battery pack protection and optimization management. The protection management of the battery pack consist of the electrical and the thermal protection. The electric protection includes battery protection for fixed battery use in safe operating area (SOA) condition, so that the battery does not get damaged quickly. The electric protection is monitoring battery pack current and cell module voltage. The electrical SOA of any battery cell is bound by current and voltage. The best of the BMS design will protect the battery pack by preventing operation outside the manufacturer's cell ratings. It involves current control to reside within the SOA zone and to improve lifetime battery.

The SOA zone is determined based on the intrinsic chemistry of the selected battery cell and the cell temperature at any given time. Battery packs experience significant current from charging and discharging, so the SOA limits are limited to optimize battery life. The BMS must make decisions based on these thresholds. As shown in Fig. 2a., the BMS requests a gradual reduction of the charging current or stops the charging current. If it reaches the max current limit when a high voltage limit occurs, while approaching the low voltage limit, the BMS reduces its current demands. The BMS can also control the battery temperature through heating and cooling. Heating occurs when the BMS to flow heat energy to the battery pack. while cooling to minimize the performance loss of the battery pack. As shown in Fig. 2b., suppose the battery operates optimally at 20^0 C, if the temperature of the package increases to 30^0 C, its performance efficiency can be reduced by as much as 20%. If the pack is continuously filled and refilled at 45^0 C, the performance drop can increase to up to 50%. Battery life can also experience premature aging and degradation, if it is constantly exposed to excessive heat, especially during rapid charge and discharge cycles.

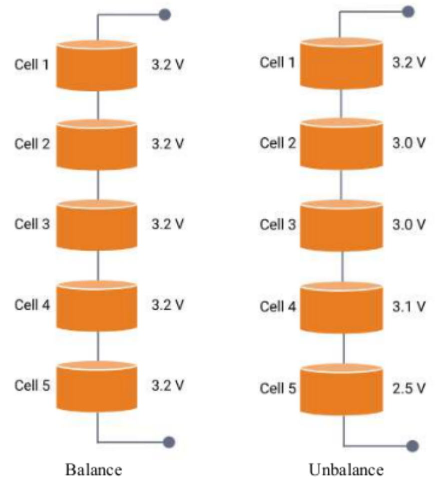
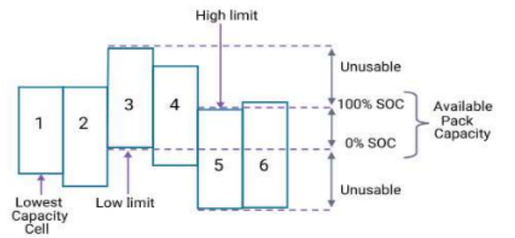


Fig. 3. Balance-unbalance condition of the battery pack.

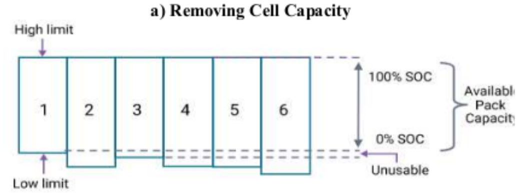
The optimization management of the battery pack is maximizing battery capacity. Initially the battery pack has good cells, but over time the storage capacity of each cell decreases. This is due to self-discharging, charge and discharge cycles, high temperatures and general aging time. The rate of self-discharging is different in each cell. As seen in Fig. 3., The arrangement of the battery pack series cells is to determine the overall package voltage (balanced) and the mismatch between cells (unbalanced). Balanced 20V battery stack when each cell is charged to 4V cut-off. If you have a perfectly balanced set of cells, all is well because each will charge 3.2V in the same way, and the charging current can be cut off when the peak voltage threshold is reached. But for unbalance 20 V battery stack may reach 18.8V when fully charged. The top cell will reach its charging limit early, and the charging current is stopped the underlying has been charged to full capacity, but there is a cell charging voltage less than 3.2V.

III. The Energy Optimizing Technique

The optimization management of BMS is about balancing the SOC variations across each stack in the battery pack. The SOC is not a quantity that can be measured directly, the SOC can be estimated by the balancing techniques. The balancing allows each cell in the stack to have the same charge capacity as the weakest cell. The BMS balances the battery stack by looking at the charging current of each cell in a different stack. The balancing is by: a) removing charge from the most charged cell, providing a major space for additional the charging current to the prevent overcharging, and allowing the undercharged cell to receive more charging current (Fig. 4a). b) diversion of some or all of the charging current around the most charged cell thus allows the undercharged cell to receive charging current for a longer period of time (Fig. 4b).



a) Removing Cell Capacity



b) Diversion Cell Capacity

In order to prevent the cell of voltage, current and temperature from exceeding the specified SOA limits during charge and discharge operations, the voltage thresholds are strictly monitored for cell protection and functional safety. To optimize the electrical capacity of the battery, all cells in the battery pack must be balanced. It also helps prevent degradation and reduces the potential for heat from overcharging weak cells.

Some things that must be considered from the characteristics of lithium-ion batteries, include; avoid discharge below the low voltage limit as this can result in significant capacity loss. Then when the ambient temperature drops (less than 5^0C), the available battery capacity and energy will decrease significantly as a result the cell cannot be charged quickly. So ensure the operating range is at 30-35^0C to maintain performance, increase life and promote a healthy and reliable battery pack. Lastly, when the cell is fully charged, the cell cannot receive any more current, the cell cannot handle overcharging well. The additional energy will be converted into heat so that the voltage has the potential to rise quickly. This can cause permanent damage and unsafe operating conditions if continued.

The following are the battery capacity optimization efforts proposed in this paper, consisting of; a) the protection function of the BMS by ensuring all cells are in SOA (for current, voltage, temperature) conditions, balancing each cell by equalizing the SOC of cells in the battery pack, and determining variations in discharge, charge and discharge cycles, temperature effects, and lifetime. The protection function of the BMS involves current control to reside within the SOA zone and to improve storage lifetime battery and reliably. b) the monitoring function, continuous monitoring of all battery cells. This is done by creating an algorithm to estimate the SOC of all cells in the battery pack, indicating the available energy, estimating the lifespan based on current usage, and estimating the SOH of the battery pack. c) the optimization function with applied LQI control for current control by adding integrator at input BMS system.

For optimization purposes, the following is a description of the characteristics of lithium batteries depicted in the Thevenin circuit as shown in Fig. 5. The battery source in the form of DC voltage is called voltage open circuit (VOC), and there is a SOC function that is connected serially [6], [7], [5].

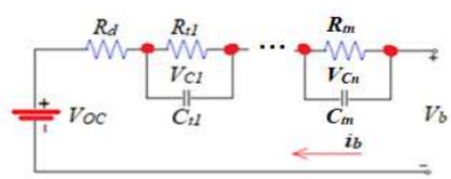


Fig. 5. Battery lithium-ion circuit [7] [5].

Referred to Fig. 5, the terminal voltage equation illustrated as: (for 1 to n-terminal) [5]

$$\frac{dV_{c1}(t)}{dt} = -\frac{1}{R_{t1}C_{t1}}V_{c1}(t) + \frac{1}{C_{t1}}i_b(t)$$
$$\vdots$$
$$\frac{dV_{cn}(t)}{dt} = -\frac{1}{R_{tn}C_{tn}}V_{cn}(t) + \frac{1}{C_{tn}}i_b(t) \quad (1)$$

with R_{t1} and R_{tn} are 1st and to n-terminal resistance. C_{t1} and C_{tn} are 1st and to n-terminal capacitance. i_b is the battery current. The voltage open circuit equation (from 1 to n) can write $V_{OC,serial}(t) = V_{OC1}(t) + V_{OC2}(t) + \cdots + V_{OCn}(t)$, where;

$$V_{OC1}(t) = a_{11}SOC_1(t) + a_{01}$$
$$\vdots$$
$$V_{OCn}(t) = a_{1n}SOC_n(t) + a_{0n} \quad (2)$$

with a_{11}, a_{1n}, a_{01}, a_{0n}, SOC_1, and SOC_n are 1 to n-battery terminal voltage when SOC at 100%, 1 to n-battery terminal voltage when SOC at 0%, and 1 to n-state of charge, respectively. The SOC equation (from 1 to n) is:

$$SOC_1(t) = (1 + SOC_{1m}(t))\ x\ 100\%$$
$$\vdots$$
$$SOC_n(t) = (1 + SOC_{nm}(t))\ x\ 100\% \quad (3)$$

SOC_{1m} and SOC_{nm} are the 1 to n-SOC change from 100% to m-condition. It can be written in the deferential equation as follow:

$$\frac{dSOC_{1m}(t)}{dt} = -\frac{1}{Q_{1m}}i_b(t)$$
$$\vdots$$
$$\frac{dSOC_{nm}(t)}{dt} = -\frac{1}{Q_{nm}}i_b(t) \quad (4)$$

Q_{1m} and Q_{nm} are 1 to n-capacity battery at m-condition. The state of health (SOH) equation is [8], i_c is the charging current.

$$\frac{dSOH_1(t)}{dt} = \frac{1}{Q_m}i_c(t)$$
$$\vdots$$
$$\frac{dSOH_n(t)}{dt} = \frac{1}{Q_m}i_c(t) \quad (5)$$

The battery voltage equation can be written:

$$V_b(t) = V_{OC,serial}(t) - R_d i_b(t) - V_{c1}(t) - \cdots - V_{cn}(t) \quad (6)$$

with R_d is the internal resistance.

Based on (1) and (4), defined that the state variable is $x_1(t) = \boldsymbol{V_c}(t)$, $x_2(t) = \boldsymbol{SOC_m}(t)$, and $x_3(t) = \boldsymbol{SOH}(t)$ the control variable is $u_1(t) = i_b(t)$ and $u_2(t) = i_d(t)$. While $\boldsymbol{V_c}(t) = \begin{bmatrix} V_{c1} & 0 & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & V_{cn} \end{bmatrix}$, $\boldsymbol{SOC_m}(t) = \begin{bmatrix} SOC_{m1} & 0 & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & SOC_{mn} \end{bmatrix}$, $\boldsymbol{SOH}(t) = \begin{bmatrix} SOH_1 & 0 & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & SOH_n \end{bmatrix}$.

The state variable is $x_1(t) = \boldsymbol{V_c}(t)$, and $x_2(t) = \boldsymbol{SOC_m}(t)$, the control variable is $u(t) = i_b(t)$. The state space of the battery system illustrated as follow:

$$\dot{x}(t) = Ax(t) + Bu(t) \quad (7)$$
$$y(t) = Cx(t)$$

with $\boldsymbol{A} = \begin{bmatrix} A_1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$, $\boldsymbol{B} = \begin{bmatrix} \frac{1}{C_t} & 0 \\ -\frac{1}{Q_m} & 0 \\ 0 & \frac{1}{Q_m} \end{bmatrix}$, $C = [1 \quad 0 \quad 0]$, and $A_1 = -\frac{1}{R_t C_t}$.

SOC and SOH cannot be measured, but can be estimated based on battery current. An energy optimization can be done by adjusting the current battery. In this paper, we apply the LQI controller [5]. Referred to (7) given the tracking reference $\dot{x}_i(t) = r(t) - Cx(t)$, the augmented equation is obtained as follows:

$$\dot{x}_z(t) = A_z x_z(t) + B_z u(t) + G_z r(t) \quad (8)$$

with $A_z = \begin{bmatrix} \boldsymbol{A} & 0 \\ -C & 0 \end{bmatrix}$, $B_z = \begin{bmatrix} \boldsymbol{B} \\ 0 \end{bmatrix}$, $G_z = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$, and $x_z = [x \quad x_i]^T$

The control feedback signal is

$$u_c(t) = -K_z x_z(t) = -kx(t) - k_i x_i(t) \quad (9)$$

with $K_z = -R^{-1}{B_z}^T P$, and matrix P obtained from solving the following algebraic Riccati equations:

$$Q + {A_z}^T P + P A_z - P B_z R^{-1} {B_z}^T P = 0 \quad (10)$$

Conditions for the weighting matrix R>0 and Q≥0. The performance index as follow:

$$J = \int_0^\infty (x_z(t)^T Q x_z(t) + u_c(t)^T R u_c(t))\, dt \quad (11)$$

To measure energy use (12) for charging and (13) for discharging with the battery voltage in (5), as follows:

$$E_c(t) = \int_0^\infty V_b(t) I_b(t)\, dt \quad (12)$$

$$E_d(t) = \int_0^\infty V_b(t) I_d(t)\, dt \quad (13)$$

Next to determine the storage lifetime battery can be calculated through the total transferable energy (TE_{tot}) in (14) and the used battery power (BP_{use}) in (15) [1], [2].

$$TE_{tot} = 2 \times C_d \times D \times Bp \times \eta^2 \quad (14)$$

$$BP_{use} = 2 \times D \times Bp \times day \quad (15)$$

$$lifetime = \frac{TE_{tot}}{BP_{use}} \quad (16)$$

with C_d is the achievable cycle at the selected DOD, D is the selected DOD, Bp is the battery power, and η is the efficiency. One cycle is defined as the operation of charging and discharging to the amount of selected DOD from the maximum SOC. The cycle number is a function of operating temperature and designed by a polynomial equation of 3rd order as

$$C_L = aT^3 - bT^2 + cT + d \quad (17)$$

where a, b, c, and d were empirical coefficients of the least square, there are 0.0039, 1.95, 67.51, and 2070, respectively [9].

IV. Test Setup and Discussion

A test setup is a characteristic test on the BMS and battery. The battery used (Fig. 6) has a nominal voltage of 36V and the total capacity of the battery pack is 14.4Ah. The battery consists of 12 cells, each cell has a voltage of 3.2V and is serially installed. The battery power is selected as 8.64KW. The charging is performed for 1 hour by 1^0C rate (temperature) and the discharging is performed for 2 hours at 0.5^0C-rates. The battery current limit at 6A (discharging) and 15A (charging). The battery voltage limit at 2.4V to 4V for each cell. The operating temperature range is 30-35^{0}C. The battery is connected to the BMS with a distributed BMS architecture (Fig. 6). A distributed BMS incorporates all the electronic hardware on a control board placed directly on the cell that is being monitored. This alleviates the bulk of the cabling to a few sensor wires and communication wires between adjacent BMS modules. Consequently, each BMS is more self-contained, and handles computations and communications as required.

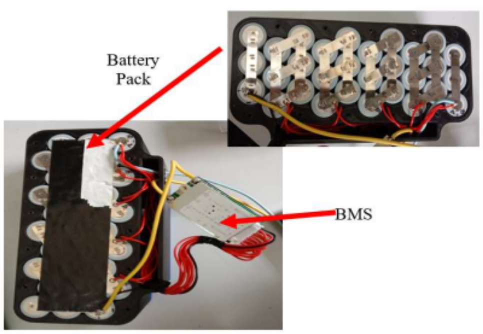
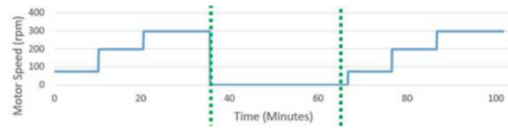
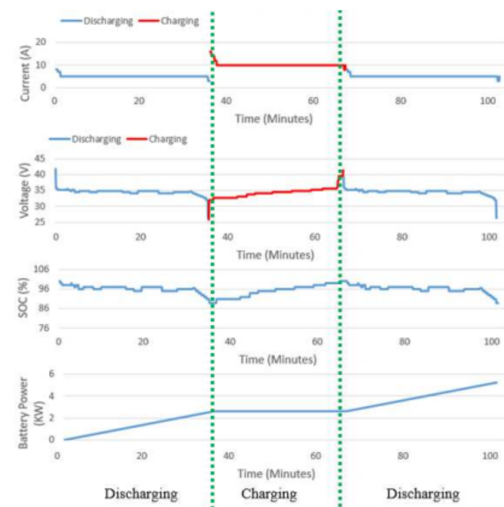


Fig. 6. Test setup.

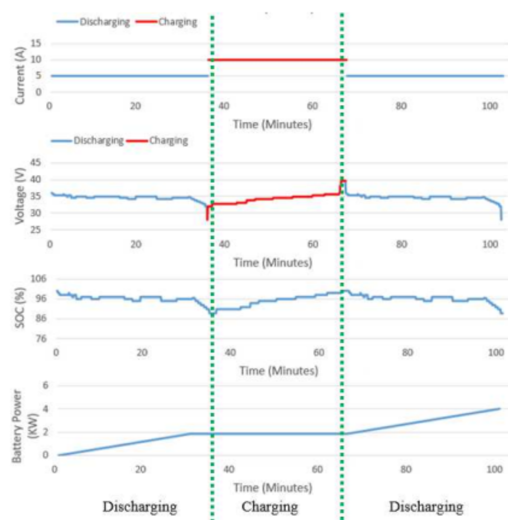
For test setup purposes, the load connected to the battery is a 350W electric motor, which has three speed modes, namely 75rpm (low), 200rpm (medium), and 300rpm (high). The test was carried out by varying the speed for about 13 minutes for each speed mode (Fig. 7a). In one experimental range, the battery provides a voltage source to the load (electric motor) for 35 minutes, this is called the discharging process. Then charging the battery for about 30 minutes. In this test and measurement, which had time to discharging the battery by providing a load with the same mode variation 10 times a day until the battery voltage reached 18V, then charging it to full battery capacity with a voltage of 36V after about 3 days later. Based on the measurement results of charging and discharging currents shown in Fig. 7b. It was found that the charging current is around 15A (red line) and the discharging current is around 5A (blue line), this is still within the SOA limit, so the inrush current is safe. Likewise, for the battery voltage is still within the safe limits of about 28V-40V. The SOC can be calculated based on (3) and measured by the current, so the change in battery charge can



(a) The Variance of the Motor Speed



(b) Test Setup Result



(c) Simulation with LQI Control

be seen in Fig. 7b. However, it can be seen that the battery voltage and current have a slight surge in current and voltage, this causes the battery power to reach 5.26KW. Battery power is calculated based on the current using the battery (discharging) to the battery voltage and the time used.

Based on the results of these tests and measurements, simulations are then carried out to obtain responses from the characteristics of the battery using computing and battery modeling for (1) to (7). Assuming the value of the terminal resistance (1.72mΩ), the internal resistance (11mΩ), and the terminal capacitance (1.2F) is the same, then based on equation (7), the matrix for each cell is $A_1 = [-0.48]$, matrix B for charging $\boldsymbol{B_c} = [0.83 \quad -0.069 \quad 0]^T$, and matrix B for discharging $\boldsymbol{B_d} = [0 \quad 0 \quad 0.0069]^T$.

Then the LQI control design is carried out to adjust the battery current by adding an integrator outside the BMS system. Based on (8) to (11) the values of LQI feedback gain for each cell are $K_{zc} = [0.28 \quad 0.32 \quad 0.81 \quad -0.29]$ for charging condition, and $K_{zd} = [3.19 \quad 1.14 \quad 2.03 \quad -2.91]$ for discharging condition. By implementing LQI controller on the BMS module, it can be seen in Fig. 7c that the battery current and battery voltage spikes can be reduced, thus the battery power used is reduced by about 4.05 KW. Thus battery energy can be saved about 29.87%.

Referred to (17) a good cycle process is estimated at around 2,103.27 cycles. Battery lifetime (16) is obtained from the comparison of energy transfer (14) to battery power used (15), as shown in Table I. The DOD determines the fraction of power that can be withdrawn from the battery. The DOD value is inversely proportional to SOC. Example, in 100% capacity battery if SOC 60% then DOD 40%, or vice versa. If the DOD of a battery is given by the manufacturer as 40% then only 40% of the battery capacity can be used by the load. Transfer energy is energy that can be given to the load, so the battery will experience a voltage drop (5V to 4.5V etc.). Thus the energy transfer value for the DOD battery conditions is different.

TABLE I. RELATIONSHIP DOD WITH LIFETIME BATTERY

SOC (%)	DOD (%)	Transfer Energy (KW)	Battery Power used (KW)	Lifetime Battery (%)
90	10	0.05	7.46	82.9
80	20	0.08	6.72	81.7
70	30	0.09	5.97	79.9
60	40	0.105	5.22	77.6
50	50	0.09	4.48	74.8
40	60	0.113	3.73	75.9
30	70	0.117	2.98	64.8
20	80	0.12	2.24	59.9
10	90	0.123	1.49	46.4
0	100	0.128	0.75	33.3

The battery power or the battery capacity is a unit indicates how much electric power can be used over time. The battery lifetime is estimated by a manufacturer or the number of charge cycles until the end of useful life. Like the example in Table I, the battery will transfer energy to the load when the DOD is 40%, then the energy transfer capability is 0.105KW. with available battery power based on an estimated 60% SOC, this equates to a stored 5.22KW battery capacity and an estimated lifetime of about 77.6%, usable energy. As for Table II, for 40% DOD with the same energy transfer capability as the previous one, it gets 5.45KW battery power for 60% SOC and estimated lifetime of around 79.92%. Thus the lifetime battery improve is about 28.11% for the BMS with the LQI controller compared to BMS without controller.

TABLE II. DOD VS LIFETIME BATTERY WITH LQI CONTROL

SOC (%)	DOD (%)	Transfer Energy (KW)	Battery Power used (KW)	Lifetime Battery (%)
90	10	0.05	7.79	85.22
80	20	0.08	7.01	84.01
70	30	0.09	6.23	82.22
60	40	0.105	5.45	79.92
50	50	0.09	4.67	77.12
40	60	0.113	3.89	78.22
30	70	0.117	3.12	67.12
20	80	0.12	2.34	62.22
10	90	0.123	1.56	48.72
0	100	0.128	0.77	35.62

V. CONCLUSION

The BMS battery pack of the protection and optimization function has been proposed. The protection management of The BMS battery pack is protected by preventing operation outside that It involves current control to reside within the SOA zone and to improve lifetime battery. The optimization of the BMS battery pack indicates optimize the amount of energy than can be derived from the battery, and also how much the battery pack can be charged. The BMS with the LQI controller can be reduced battery current and voltage spikes. Thus it is potential to improve storage lifetime by about 28.11% and energy optimization by about 28.87%.

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Energy Optimized of an Electric Vehicle Battery Management System to Improve Storage Lifetime

Publisher: IEEE Cite This PDF

Rina Ristiana ; Amin ; Rina Mardiati ; Aam Muharam ; Abdul Hapid ; Alexander Christantho Budiman ; Sudirja ; Sunarto Kaleg All Authors

Abstract:
The BMS battery pack of the protection and optimization function has been proposed. The protection function of BMS involves current control to reside within the SOA zone and to improve storage lifetime battery by about 28.11% and reliability. The optimization function with applied LQI control to adjust the battery current by adding an integrator at the module BMS system. The BMS with LQI controller has been to improve storage lifetime battery with eliminate current stepping and getting energy_optimized about 28.87% with considering the battery condition.

Published in: 2022 8th International Conference on Wireless and Telematics (ICWT)

Date of Conference: 21-22 July 2022

Date Added to IEEE *Xplore*: 07 November 2022

▸ ISBN Information:

INSPEC Accession Number: 22238753

DOI: 10.1109/ICWT55831.2022.9935453

Publisher: IEEE

Conference Location: Yogyakarta, Indonesia

https://epeneliti.brin.go.id/jurnal?nama=2021+7TH+INTERNATIONAL+CONFERENCE+ON+WIRELESS+AND+TELEMATICS+%28ICWT%29&tahun=2021

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